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ORIGINAL ARTICLE

Integration Analysis of Electric Vehicle Charging Station Equipped with Solar Power Plant to Distribution Network and Protection System Design

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Abstract
The improvements and implementation of new generation equipment to the conventional grids are increasing along with the increase of the number of renewable energy power plants and smart grid components. The existing grid infrastructure is required to be modified and upgraded as a result of the increasing integration of the renewables and new generation consumers where the availability of the existing networks has to be analyzed for integration as well. In order to keep the grid stable and integrate the renewables to the grid optimally, necessary analyses have to be realized including the investigation of the optimal integration criteria. During the integration phase of the new generation consumers and producers, two ways power flows and variable power production of renewables have to be considered for system design. In this study, analysis for optimal sizing and integration studies are performed for electric vehicle parking lot and solar power plants located on the campus distribution network considering optimal sizing criteria and the aim of stabilization of voltage regulation during day time operation of solar power plant and random charging profile of electric vehicles. The proposed network is equipped with adaptive protection system to ensure stability and the reliability of the distribution network in the concept of smart grid.

Keywords Electric vehicles · Solar power plants · Grid integration · Smart grid · Distribution network

Abbreviations

DG	Distributed generation
ETAP	Electrical transient analyzer program
EV	Electric vehicle
IEC	International electrotechnical commission
LV	Low voltage
MV	Medium voltage
PV	Photovoltaic
SPP	Solar power plant
YTU	Yildiz technical university

Indices

h	Set of EVs
t	Set of time

Variables

CE_h	Charging efficiency of the charging station connected to EV h
P_t	Charging power of EV h in the period of t
SoE	State of energy
$SoE_{h, T}$	SoE value of EV h in the period of t

Parameters

c	The voltage factor that accounts for the maximum and minimum system voltage
D_t	Time granularity, interval duration
I	Expected fault current
I_k	The initial symmetrical short circuit current
I_s	Relay pick up current
t(I)	Trip time
TMS	Time multiplier setting
V_n	Nominal system voltage
Z_k	Equivalent positive sequence short circuit impedance

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1 Introduction

The usage of electric vehicles (EVs) and the solar power plants (SPPs) are being widely increased as a result of improvements in the technology and environmental concerns where the new generation elements of the integrated components come up with the requirements for distribution networks and protection systems. The proposed challenges for integration of new generation systems cover the titles of stabilization of distribution networks during two way power flow and variable power generation of SPPs. Increasing the number of renewables on the grid will be most effective way to reduce carbon emissions [1]. However, increasing penetration of EVs and SPPs may cause disturbance on the network based on the variable power generation of SPPs and the unpredictable consumption characteristics of EVs where successful coordination of the SPPs could improve reliability of the network with the advantages of peak load shaving [2]. Uncertainty of generation may cause problem at small scale distribution networks such as campus areas [3]. Smart grid technology can be the solution to deal with the challenges within a city caused by proposed EV and SPP systems [4]. The disturbance caused by EVs and SPPs may lead to faults at the protection system due to fixed set points of the protection relays. One of the major drawbacks in such systems is the oscillating nature of renewable energy plants [5]. The drawbacks caused by such system design may cause loss of energy along with economic impacts. The major challenges of EV integration on the perspective of grid stability are presented in [6].

In this context, integration process is to be realized by following a methodology that provides the opportunity of reliable and efficient operation. The optimal sizing of EV charging stations and SPPs is considered as the first stage of the proposed methodology considering the physical limitations of the distribution network area. The impact of uncoordinated EV charging must be considered until smart charging systems become available [7].

The strategies for charging coordination in the concept of multi agent based modeling are investigated in [8] where large scale EV charging station studies are performed in [9, 10] along with the metaheuristic optimization algorithms are adopted to control system in [11, 12]. Operational scheduling studies to optimize EV charging schedules are performed in [13] for EV parking lots where the affect of EV charging sequences on the network are presented in [14]. A sudden increase on the demand caused by EVs caused by same time charging may cause problems [15]. Strategies for charging planning and optimization are presented in [16–18]. Optimal planning strategy should be presented along with network area limitations and requirements to design such reliable and efficient network. EV demand may cause distortion at network at high integration level, the strategies for EV charge scheduling and peak load studies are presented in [19–21]. Studies for EV charging strategies based on scheduling are presented in [22]. An operator controlled infrastructure based on hierarchical approach for the grid and the generation units is presented in [23].

The major changes driven by the environmental concerns led to increasing penetration of the renewables where the complexity of the network is increased rapidly. The proposed new generation grid components required to be assessed carefully before the integration stage [24]. A methodology to reduce peak loading of EVs using charging strategies is presented in [25] where control based approach is presented in [26]. The effect of high level EV integration is presented in [27] from the distribution network perspective, renewable and EV operation strategies are presented in [28], an optimized EV scheduling model is presented in [29]. Smart charging infrastructures for the large scale EV integration are presented in [30]. Control algorithm based applications are investigated to reduce EV impact on the grid [31]; however the impact of the EV demand may fluctuate due to unpredictable behavior of the consumers.

The major drawback of the networks equipped with SPPs and EV charging stations are unpredictable power generation data and EV power consumption caused by EV user profile. EV consumption may affect the distribution network in a wide range at small distribution networks, where the effects are presented in [32]. In order to obtain a reliable network infrastructure on a large scale renewable and EV integrated grids, energy management approaches and control algorithms are presented in [33]. The combinational operation of EV charging stations and SPPs based on randomized charging sequences of EVs and prediction based SPP generation is presented in [34]. DG based networks present the advantage of reliable and efficient power generation along with the additional requirement of control systems. A coordinated power management and control algorithm is presented in [35] to provide necessary control system for the DG networks.

In this context, in this study the model of Yildiz Technical University (YTU) Davutpasa Campus network is designed and simulated in Electrical Transient Analyzer Program (ETAP) environment to obtain normal operation conditions of the distribution network. The campus network model is equipped with EV charging stations and roof mounted SPPs in accordance with physical and electrical limitations considering optimal sizing criteria. The modeled EVs and SPPs are integrated to campus network to simulate day time power consumption of randomly selected EVs and variable power generation of SPPs in accordance with winter solar radiation data of Istanbul, Turkey. The study consists of two cases which are the impact of EVs on campus grid without usage of SPPs to augment power generation as Case 1, implementation of SPPs to the grid and indication how they help augment as the Case 2.

The simulation results and effect of optimal integration of proposed system to the network is applied to model to obtain protection settings for all scenarios including normal operation cases and worst case scenarios. Finally, the results of integrated model and the effects on the network are presented with optimized protection relay settings and system response for fault analysis where the overcurrent relays are modeled in accordance with IEC 60,255 standards [36].

The proposed study aims to realize elimination of drawbacks of EVs and SPPs integrated grid in the concept of restoration of voltage stability and reduction of relay operation duration which is effected by variable generation and consumption characteristics of the network. The major contributions of the realized study can be listed as:

- The study contains optimal integration analysis for EV charging stations and SPPs within physical and electrical limitations of the distribution network based on network integration criteria.
- EV and SPP characteristics are modeled including randomly generated EV consumption and solar radiation data based SPP generation for day time operation.
- The network model equipped with SPPs and EVs is optimized to obtain stability for voltage regulation of the network with proposed methodology.
- The network model and components are equipped with adaptive protection system where the adaptive settings are obtained from study cases and scenarios of day time operation of SPPs and EVs.

The remainder of the study is organized as follows: System methodology and simulation results are indicated in Sect. 2 where the study results and main contributions are indicated in Sect. 3 along with the conclusions in the Sect. 4 of the paper.

2 System Methodology and Simulations

The campus network consist of faculty substations and parking lots for EV charging station design along with roof mounted photovoltaic (PV) panels, however the parking lots are not equipped with charging stations in current situation. The campus network and physical limitations of the campus parking lots and roofs are investigated for sizing studies where an analysis for sizing and optimization studies is performed. The existing network model is considered as electrical limitation criteria including transformer, bus, switchgear and cable ratings. SPPs and EVs are integrated to existing network in ETAP environment to observe the effect of proposed model on the distribution network for various scenarios. The power consumption of EVs with hourly intervals is applied to network along with the hourly variation of average solar radiation for SPP power generation. The existing model of the campus is indicated in Fig. 1.

The campus ring network consists of 12 substations for each faculty and a main medium voltage (MV) substation, where the voltage level of the network is 34.5 kV and each faculty building is equipped with 34.5/0.4 kV transformers. Faculty transformers are connected to relevant low voltage (LV) switchgears where proposed EV charging stations and roof mounted SPPs are connected. Typical schematic for faculty network is indicated in Fig. 2.

As the first stage of the study, sizing studies are conducted for the SPPs and EVs considering physical limitations and availability factors of the campus infrastructure. The mounting surface limitation of the SPPs, bus ampacity and electrical limitations of the substations are considered for design criteria. SPPs and EV charging stations are modeled in simulation environment considering physical and electrical limitations of the campus and the distribution network. The SPPs are designed in accordance with optimal sizing criteria and connected to relevant LV bus for each faculty building. After the design stage of SPPs, solar radiation data is applied to each SPP to

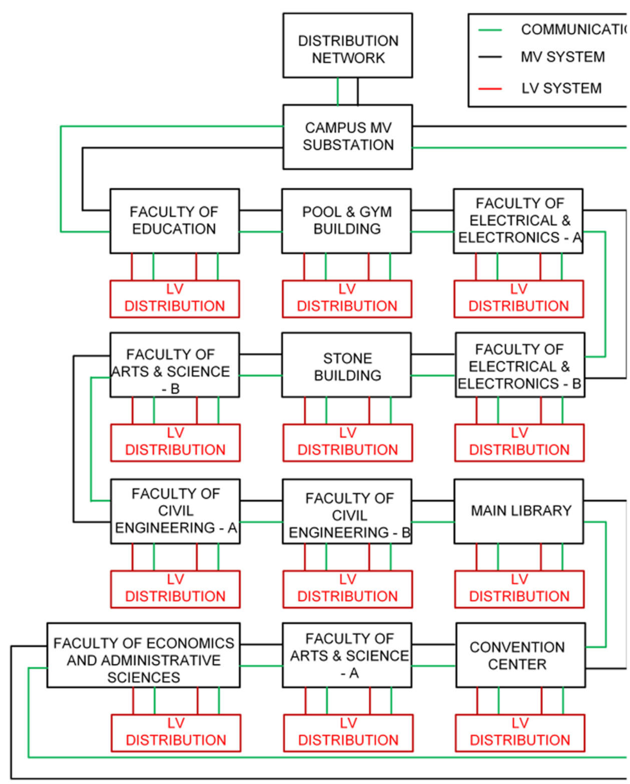

Fig. 1 YTU Davutpasa Campus network model

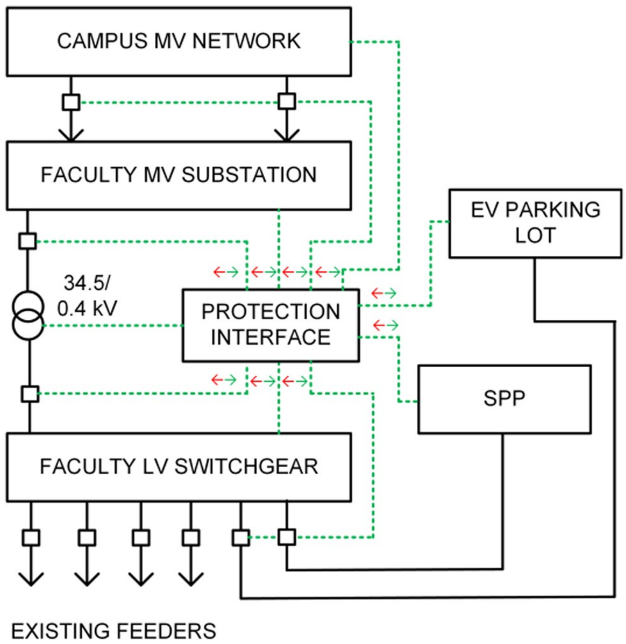

Fig. 2 Typical faculty substation model

Table 1 Installed SPP and EV capacities

No	Substation ID	SPP Capacity	Car Capacity
1	Faculty of education	270 kVA	194
2	Pool & gym building	180 kVA	84
3	Faculty of electrical & electronics–A	504 kVA	74
4	Faculty of electrical & electronics–B	315 kVA	113
5	Faculty of arts & science–B	774.1 kVA	177
6	Stone building	828 kVA	168
7	Faculty of civil engineering–A	540 kVA	276
8	Faculty of civil engineering–B	467.9 kVA	46
9	Main library	126.1 kVA	53
10	Convention center	440.9 kVA	201
11	Faculty of arts & science–A	899.9 kVA	299
12	Faculty of economics and administrative sciences	315.1 kVA	285

determine day time power generation and base consumption of the faculty buildings. Obtained results for EV parking lot capacity and SPP generation ratings are indicated in Table 1.

The SPP and relevant elements of the SPP are designed in accordance with network requirements and sizing criteria. PV module parameters are indicated in Table 2. The final stage of SPP design is the implementation of the solar radiation data to SPPs along with day time solar radiation variation which is limited between sunrise and sunset period. The 3 months average solar radiation data of winter season is

Table 2 PV panel design data [37]

Panel ID	Power (W)	Vdc Max (V)	Power Tolerance (%)
STP280-24-VD. STP275-24-VD	280	600	5

Table 3 Solar radiation data

Time	Average solar radiation (W/M^2)	Time	Average solar radiation (W/m^2)
06:00	158 W/m^2	14:00	907 W/m^2
07:00	520 W/m^2	15:00	889 W/m^2
08:00	696 W/m^2	16:00	855 W/m^2
09:00	794 W/m^2	17:00	798 W/m^2
10:00	852 W/m^2	18:00	704 W/m^2
11:00	887 W/m^2	19:00	534 W/m^2
12:00	906 W/m^2	20:00	185 W/m^2
13:00	912 W/m^2		

Table 4 Charging power and capacity of Modeled EVs

Model of the car	Battery capacity (kWh)	Charging power (kW)
Volkswagen E-Golf	24	7.2
BMW i-3	22	6.6
Mercedes B-Class	28	10.0
Tesla Model–S	85	17.2
Fiat 500E	24	6.6
Ford Focus Electric	23	6.6
Kia Soul EV	27	6.6
Mitsubishi i-MiEV	16	3.3
Chevy Volt	17	3.3
Nissan LEAF	24	6.6

indicated in Table 3 which is between December and February to simulate the worst case energy production.

EV charging stations are located close to each faculty which is currently being used as parking lots for fossil fueled cars. The EV charging station feeders planned to be connected to relevant faculty LV substation due to availability of currently installed switchgears. EV parking lot capacity is decided in accordance with physical and electrical limitations of the LV switchgears and transformers. The modeled EVs are listed in Table 4 which are randomly selected to obtain random consumption profile for each faculty with random arrival and departure durations.

Total power consumption of EVs is limited with the capacity of parking lot and selected car battery capacity and charging power. The arrival and departure durations of the EVs are limited within the range of 6 am to 8 pm. EV consumption profile is calculated considering the EVs are at minimum state of energy (SoE) when the cars arrive to the parking lot and the cars are being charged till its full capacity to simulate worst case loading scenario. The SoE of each EV is calculated using (1) [34].

$$SoE_{h,t} = SoE_{h,t} - 1 + CE_h * P_t * D_t \tag{1}$$

where h is the set of EVs, t is the set of the time, $SoE_{h,t}$ is the SoE value of EV h in period t, P_t is the charging power of EV h in period t, CE_h is the charging efficiency of the charging station connected to EV h and D_t is the time granularity, interval duration.

Total power consumption of EVs for each faculty is calculated and implemented to simulation environment. Obtained consumption profiles are indicated in Fig. 3.

The consumption profiles of EVs are applied to simulation environment to obtain the results for EV charging station operation which is considered as the first scenario. The voltage regulation of the campus network is aimed to be kept within the range of ± 5% during EV and SPP operation while minimizing the deviation from reference voltage level. Voltage regulation at faculty buildings is indicated in Fig. 4.

The EV integration impact on the distribution network voltage level is observed after the integration stage. There is no EV consumption at 6 am in the morning where the voltage level is 98% for Pool & Gym Building and 97.2% for other substations due to the auxiliary power consumption of the buildings. However, the voltage level decreases between 2 and 5% with the impact of EV consumption during day time. The most critical impact on the voltage level occurs at the Faculty of Arts & Science at 9 am due to the EV consumption of 400 kVA where the voltage level decreases to 92.5% at Faculty of Civil Engineering with the impact of 600 kVA of EV consumption.

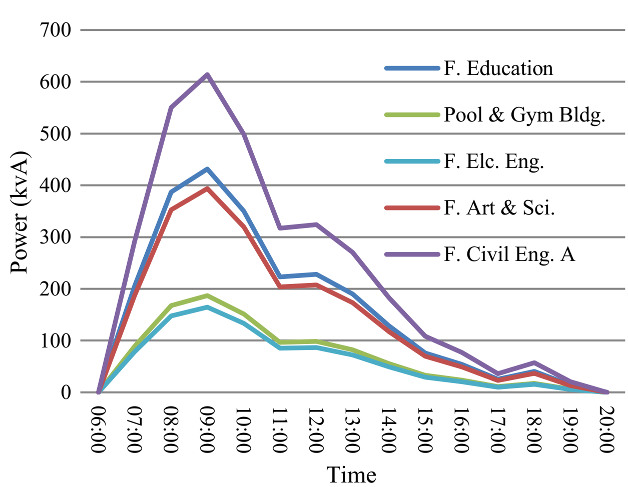

Fig. 3 EV power consumption profile

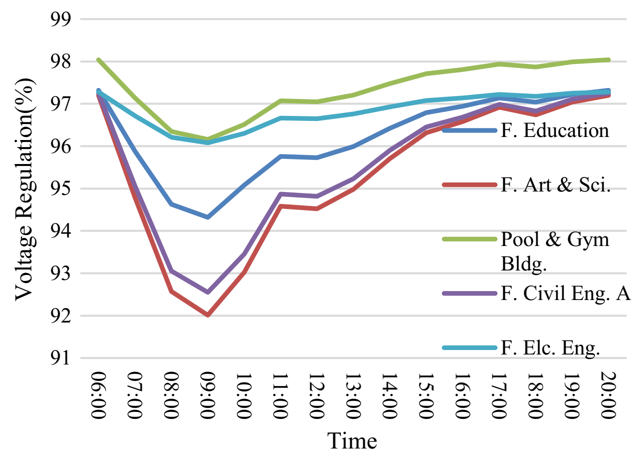

Fig. 4 Voltage regulation for Case 1

The results of the applied EV consumption profile have a significant effect on the stability of the campus network as per the simulation results and calculations. The obtained results indicate that the impact caused by the integration of EVs to the network should be eliminated to stabilize voltage level of the network. SPP integration is considered as the solution for the stabilization of voltage level considering electrical and physical limitations of the campus network. Scenario based optimized SPP sizing philosophy and the results are presented in the following section to achieve the goal of voltage stabilization of the network.

3 Simulation Results and Protection System Design

The campus network modeled and simulated with the integration of EV charging stations, where the voltage level of the network is required to be stabilized during the loading sequence of EVs. The SPPs are considered as the solution to stabilize the voltage level of the campus network. It can be stated that the voltage variation for day time EV loading has a significant effect on the distribution network and to minimize this variation, SPPs are offered to be implemented to the existing network with additional economic benefits. As the second phase of the study, calculated SPP profile is integrated to campus network as explained in Sect. 2. The second scenario includes integration of SPPs to network considering day time solar radiation variation. The simulated operation case for integrated EVs and SPPs to the network indicates that the voltage level is stabilized in accordance with optimized SPP capacity criteria where the SPP capacity is limited with the impact on the network voltage level.

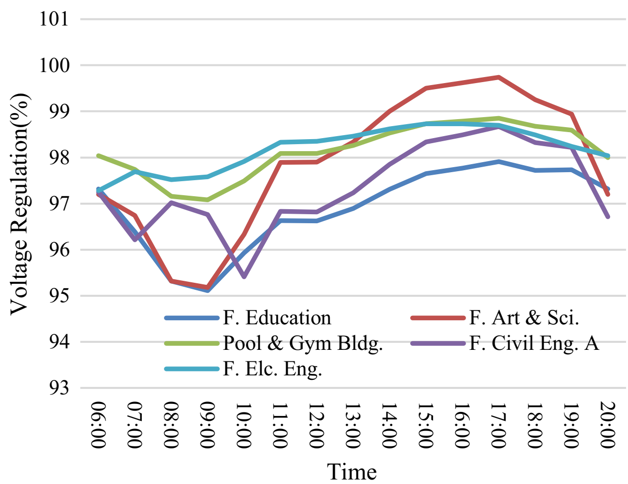

Fig. 5 Voltage regulation for Case 2

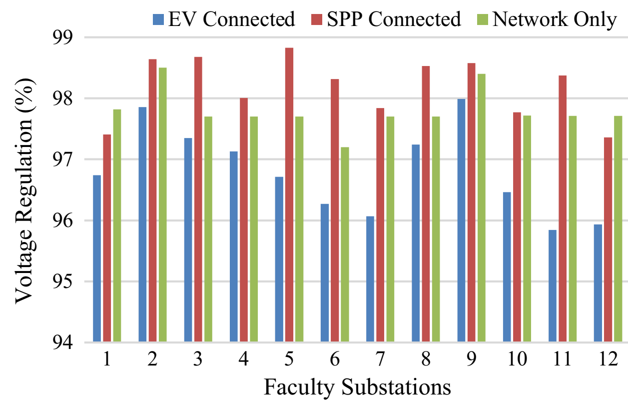

Fig. 6 Comparison of voltage regulation for 3 cases

The simulation results for the combined SPP and EV operation has a significant impact on the network considering the voltage regulation of the campus network. The generation profile of SPP has increased the voltage level which is decreased by the EV consumption profile, where the SPP generation is limited due to avoid overvoltage fault at the buses of the network. The obtained simulation results for critical and marginal voltage levels of the first case are indicated in Fig. 5 reflecting the effect of the SPP integration on the network.

The impact of the integration of SPPs on the network is observed and SPP capacity is optimized in order to avoid overvoltage and undervoltage faults on the network. The voltage regulation percentage is decreased with the integration of SPPs of faculties as indicated in Fig. 5.

The SPP generated power has led to improvement of voltage level which is aimed to be kept within the range of ± 5%. The worst decrement on the voltage level has occurred at 9 am for substation 7 and 11 as presented in the Case 1 results. The voltage level is increased by 3.1% for Faculty of Arts & Science and 2.6% for Faculty of Civil Engineering where the voltage level reaches to 95.1% for both substations.

The voltage level is investigated for the case of daily average along with momentarily voltage impact of EVs and SPP. The impact of EV consumption led to decrement of daily average voltage level to 96% and 95.8% for substations 7 and 11 respectively. The voltage level is increased to 97.9% and 98.3% with the impact of SPP for substations 7 and 11.

The less impact of EVs on the voltage level occurs at the substation 8 due to the number of EVs as presented in Table 1. The voltage level decreases by 0.3% by the impact of EV consumption where the voltage level increases by 1.3% and reaches to 98.5% with the impact of SPP.

The voltage variation comparison for EV operation, SPP operation and directly energization of faculties' base load from the grid is indicated in Fig. 6.

The obtained results indicate that voltage regulation and loading of the distribution network buses varies for each scenario where the base load operation of the campus network is considered as the first case, EV integrated operation is considered as the second case and EV & SPP combined operation is considered as the third case. For that reason, the protection system is aimed to be designed to response such network requirements.

As the last phase of the study, the obtained simulation results are applied to protection coordination algorithm in order to define relay set points to realize the aim of reliable and efficient protection system design. Circuit breakers (CBs), current transformers (CTs) and transformer ratings are applied to simulation environment in accordance with the data of campus network components. Short circuit contribution of the grid, SPPs and EVs are calculated for each operation sequence limited with hourly intervals in accordance with IEC 60,909 standards where the voltage c factors are implemented using (2) [38].

$$Ik'' = \frac{c * Vn}{\sqrt{3} * Zk} \tag{2}$$

where, I_k" is the initial symmetrical short circuit current, c is the voltage factor that accounts for the maximum and minimum system voltage, V_n is the nominal system voltage and Z_k is the equivalent positive sequence short circuit impedance. The SPP inverter models are integrated to simulation environment with the K factor of 150% to calculate initial symmetrical short circuit current where EVs are modeled as stack loads with consideration of 60% motor and 40% static loads.

The maximum and minimum short circuit levels are calculated and simulated for combined SPP and EV operation.

Maximum and minimum short circuit currents are determined using reactance tolerances, temperature correction factors and applied to simulation environment in accordance with IEC 60,909.

Short circuit current variation of maximum and minimum short circuit study cases is presented in Table 5.

Set points for protection system are calculated in accordance with standard IEC normal inverse curve as formulated in (3) [36]:

$$t(I) = \frac{0.14}{(I/Is)^{0.02} - 1} * TMS \tag{3}$$

where t(I) is trip time, I is expected fault current, I_s is relay pick up current, TMS is time multiplier setting.

Table 5 Short circuit variation for max min conditions

No	Substation ID	I_{SC} min (kA)	I_{SC} max (kA)
1	Faculty of education	20.141	25.189
2	Pool & gym building	14.518	18.197
3	Faculty of electrical & electronics–A	20.354	24.66
4	Faculty of electrical & electronics–B	20.174	24.825
5	Faculty of arts & science–B	20.614	27.329
6	Stone building	21.685	28.471
7	Faculty of civil engineering–A	20.367	28.983
8	Faculty of civil engineering–B	20.297	25.093
9	Main library	14.419	18.678
10	Convention center	20.218	27.639
11	Faculty of arts & science–A	20.649	29.256
12	Faculty of economics and administrative sciences	20.069	29.018

Faculty substations are equipped with relevant CTs, CBs, relays and communication modules for coordinated adaptive protection system design. LV substations are coordinated with each other considering SPP and EV power characteristics. The calculated protection set points are listed in Table 6.

The calculated set points are assigned to relevant relays considering the minimum TMS value as 0.05 within the limitation of protection device setting range. After the completion of calculation stage, simulation study of the protection system is conducted. The obtained results are compared with conventional protection approach and presented in Table 7 where Case A represents the conventional approach and Case B represents optimized coordination algorithm results.

Calculated relay operation sequences for the fault response time are presented in Table 7 including the communication duration and circuit breaker operation delays. Protection system of the campus model combined with EV parking lots and SPPs is analyzed for all possible scenarios and proposed algorithm is applied to set values of the relays.

The simulation results indicate that the response time of the protection system is reduced with the proposed approach for optimized coordination case. The loading percentage of EVs and SPP generated power has a considerable effect on the protection system when the voltage regulation factor is included. The comparison and reduction of operation duration is indicated in Fig. 7.

After the testing sequence of protection system for all loading cases, relay operating sequence variation is calculated and the obtained results indicate that operating duration is reduced up to 20% depending on the loading sequence and voltage factor.

Table 6 Relay set points

Trip Unit	Case 1 Nominal current (A)	Case 2 Nominal current (A)	Case 1 Relay Pick up current (A)	Case 2 Relay Pick up current (A)
Faculty of education	532.6	1125	640	1184
Pool & Gym building	271.1	530.2	640	640
Faculty of electrical & electronics–A	534	760.8	640	784
Faculty of electrical & electronics–B	532	880	640	912
Faculty of Arts & science–B	534	1113	640	1168
Stone building	680.8	1229	704	1280
Faculty of civil engineering–A	530	1448	640	1488
Faculty of civil engineering–B	533	680.7	640	704
Main library	271	441.1	640	640
Convention center	535	1193	640	1216
Faculty of arts & science–A	533.7	1528	640	1600
Faculty of economics and administrative sciences	525.8	1479	640	1504

Table 7 Protection system operation sequence

Substation ID	Case A (s)	Case B (s)
Faculty of education	0.1110	0.0980
Pool & gym building	0.1087	0.1011
Faculty of electrical & electronics–A	0.0980	0.0977
Faculty of electrical & electronics–B	0. 1025	0. 0980
Faculty of arts & science–B	0. 1076	0. 0973
Stone building	0.1094	0.0987
Faculty of civil engineering–A	0.1144	0.0977
Faculty of civil engineering–B	0.0978	0.0945
Main library	0.1089	0.1003
convention center	0.1086	0.0979
Faculty of arts & science–A	0.1170	0.0973
Faculty of economics and administrative sciences	0.1148	0.0981

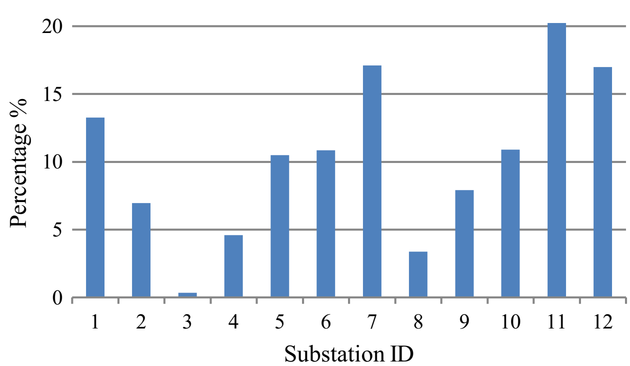

Fig. 7 Reduction of relay operation duration by percentage

4 Conclusion

In this study, YTU Davutpasa Campus distribution network is modeled and simulated including all faculty substations and base load of the faculty buildings. The network model is observed for integration of EV charging stations and SPPs considering optimal sizing criteria based on physical and electrical limitations of the campus and the network. After the integration stage, system response is observed for voltage regulation and system loading in order to apply the obtained data to protection system algorithm. The voltage regulation is aimed to be kept in limitations for safe operation and the proposed design for EV charging stations and SPPs led to maximization of SPP generation and stabilization of voltage regulation.

The study consists of cases including 3 scenarios for load flow analysis, 2 scenarios for short circuit calculations and 2 scenarios for protection coordination. The voltage regulation is stabilized with the production of SPPs and protection system is designed to respond the requirements of the network equipped with SPPs and EV charging stations.

As per the study results, grid voltage level considerably decreased with the effect of EV charging station integration which is investigated as the first case. The drawback caused by EV integration is eliminated with integration of SPPs to the network. The effect of variable loading and generation sequences on the protection system is aimed to be eliminated and adaptive protection set points are defined in accordance with system loading scenarios. The proposed protection system is compared with conventional protection approach and the results indicate that the duration of protection system is reduced by 20% at Faculty of Arts & Science substation, where the loading and voltage regulation is highly variable. The increasing usage of EVs and SPPs will have a significant effect on the distribution networks and the protection systems as observed in the study. The proposed system design can respond the system needs considering reduction of voltage regulation, line losses and carbon emission as well with a reliable protection system. The proposed system is planned to be equipped with load sharing modules in future studies.

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